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Microplastic contamination of intertidal sediments of Scapa Flow, Orkney: a first assessment

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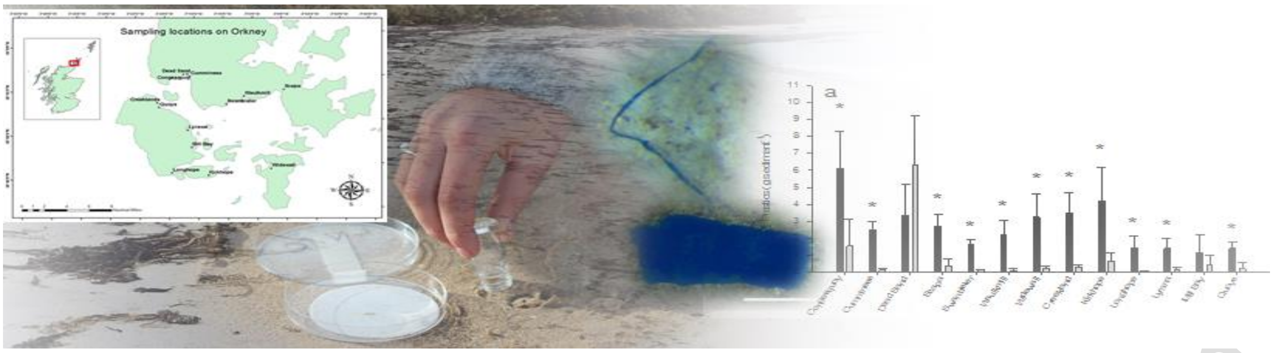
Abstract

The concentration of microplastic particles and fibres was determined in the intertidal sediments at selected sites in Scapa Flow, Orkney, using a super-saturated NaCl flotation technique to extract the plastic and FT-IR spectroscopy to determine the polymer types. Mean concentrations were 730 and 2,300 kg^{-1} sediment (DW), respectively. Detailed spatial and quantitative analysis revealed that their distribution was a function of proximity to populated areas and associated wastewater effluent, industrial installations, degree of shore exposure and complex tidal flow patterns. Sediment samples from Orkney showed similar levels of microplastic contamination as in two highly populate industrialized mainland UK areas, The Clyde and the Firth of Forth. It was concluded that relative remoteness and a comparative small island population are not predictors of lower microplastic pollution. Furthermore, a larger concerted effort across Scotland and the UK is required to establish a baseline microplastic database for the evaluation of future policy measures.



Graphical abstract

Highlights

- Microplastics extraction from intertidal sediments using a NaCl flotation technique
- Distribution governed by population density, industry and hydrographic conditions
- Concentrations of particles and fibres similar to more populated UK sites
- Inter comparison studies required to make results comparable
- Large scale and long-term surveys required for informing policy decisions

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1. Introduction

Litter contamination of the marine environment is not a new phenomenon (Barnes, 2002; Nelms et al., 2017). However, the recent emergence of public awareness, fuelled by highly successful social media campaigns (MCS, 2016; BeatTheBead, 2017; FIDRA, 2017), of the socio-economic impacts have resulted in an increased interest in the ecological risks of litter, much of which originating from plastic packaging material. The annual proportion of plastic material in debris recovered from UK beaches is increasing exponentially (MCS, 2016), and plastic litter has been found in practically all marine environments, including the deep-sea (Woodall et al., 2014), Antarctica (Barnes et al., 2010) and other remote locations (Ribic et al., 2012). The vast majority of plastic polymers do not readily biodegrade under environmental conditions, but rather erode in to ever smaller fragments, leading to the formation of microplastics (<5mm) and possibly even nanoplastics (<1µm – to our knowledge, there are currently no reports of nano-sized plastic particles recovered from field samples), much of which is deposited in sub- and intertidal sediments. Thompson et al. (2004) were one of the first research groups to describe the occurrence of microplastics in intertidal sediments, and since then reports of similar observations from around the world have proliferated - see reviews by Hartl et al. (2015), GESAMP (2015) and Besley et al (2017). Furthermore, the picture that is emerging is that local microplastic loads in marine sediments appear to be directly proportional to the annual global plastic production (Claessens et al., 2011), which has increased from an estimated 1.5 million tonnes in the 1950s to 311 million tonnes in 2014 (PlasticsEurope, 2015). The growing amount of data regarding plastic litter contamination in the marine environment has led to the need for understanding the associated risks to marine organisms and human health. Marine organisms, many of them of significant economic value, are known to interact with microplastics through ingestion (Murray and Cowie, 2011) and exposure through gills (GESAMP, 2015). This has been shown the disruption of the energy balance in marine bivalves (Xu et al., 2016) and the transfer of associated organic chemicals has been proposed by several authors (Andrady, 2011; Rochman et al., 2013), thus potentially increasing their bioavailability with subsequent toxicological implications. However, the potential risk to marine biota from contaminant transfer is still being debated and remains controversial (Koelmans et al., 2016). Consequently, pressure is growing for legislation and regulatory measures to address the problem of plastic contamination in the marine environment (Xanthos and Walker, 2017). Descriptor 10 of the European Union Marine Strategy Framework Directive (MSFD) highlights the socio-economic issues of litter as a sign of a society with a resource inefficient economy. Descriptor 10 also provides “possible” targets for reducing microplastics in the marine environment, by decreasing/slowing the rate of microplastic increase by 2020 (EC, 2008). Several initiatives have been instigated to deal with the problem at source, especially through improved waste management, a nudge culture towards a more circular economy and the reduction of single-use plastic consumer goods, such as plastic bags, campaigns consisting of organized beach cleans and “fishing for litter”. The latter involves the fishing industry retaining litter caught in nets at sea and port authorities providing the infrastructure for handling the landed material. However, this merely addresses the symptoms. The Scottish Government has recently introduced a tax on single-use plastic bags and is currently consulting on the ban of plastic microbeads in personal care products, as well as a deposit-return scheme for plastic bottles. Whether any of these policies and initiatives are likely to deliver the desired results depends on a mechanism for objectively measuring progress. This can only be achieved if a baseline is developed against which progression towards the stated goals can be gauged. Currently, no sufficient quantitative, spatial and temporal figures for intertidal sediment microplastic contamination are available to enable this (MSS, 2016), and only a patch work of data from studies in various Scottish and comparable North Sea locations exists (Browne et al., 2011; Claessens et al., 2011; Stolte et al., 2015). A systematic approach across Scotland is required applying standardized methods in order to establish such a database. Scotland has 18,000 km of coastline, including over 900 islands (Baxter et al., 2011), such as Orkney. Orkney is an inhabited island archipelago situated 16 km north off the north-east tip of Scotland, separated from the UK mainland by the Pentland Firth. It consists of 70 islands with significant economic activity focussing on marine renewable energy, crude oil processing, exporting and transfers, aquaculture and fisheries, and tourism. Orkney also has a recognized litter problem. Extrapolating from Marine Conservation Society beach clean data, an estimated 73 tonnes of mainly plastic litter accumulated on the 980 km of shore in Orkney in 2016. However, no data exist on the concentration of microplastics in Orkney intertidal sediments. Therefore, the present paper focusses on Scapa Flow, a large island-enclosed bay at the southern tip of the archipelago, with the aim of conducting a first assessment of microplastic contamination as part of larger Scotland-wide efforts to feed in to the above-mentioned database.

2. Methods

2.1. Sampling locations

Orkney is the southern of the two archipelagos of the Northern Isles, the other being Shetland, situated 59°N 3°W, approximately 16 km off the Scottish coast of Caithness (Fig 1). It is comprised of some 70 islands of which 20 are inhabited with a population of around 21,349, 75% of who live on the largest Island, Mainland, concentrated in the two main settlements of Kirkwall and Stromness (ScottGov, 2016). Scapa Flow is a shallow, approximately 300 km^2 body of water surrounded by the islands of Mainland, Graemsay, Burray, South Ronaldsay and Hoy (Fig 1). To the East, Scapa Flow is separated from the North Sea by the Churchill Barriers, artificial concourses connecting the islands of Mainland, Burray, and South Ronaldsay, restricting and redirecting the tidal flow of water entering and exiting to the West and South (Fig 2). The specific hydro-geographic conditions make Scapa Flow ideal for a variety of anthropogenic activities, ranging from shipping, oil industry-related operations (open water ship to ship transfer and the processing point for North Sea Oil at the Flotta oil terminal), fisheries and aquaculture, and tourism. The sampling sites for the present study within Scapa Flow were selected in depositional areas with a defined, relatively sheltered, sediment-dominated intertidal zone without any distinguishing features, such as large boulders or algae coverage (Figs 1 & 3c); the precise GPS positions of the sites are given in Table 1. In order to assess the effect of Orkney's relative remoteness on microplastic concentrations found, a comparison with sites in more populated areas of Scotland (Clyde and the Firth of Forth) was carried out. Orkney and Firth of Forth samples were collected in April 2016; sampling at Erskine Bridge on the Clyde occurred in February 2016.

2.2 Sediment sampling, microplastic extraction and polymer identification

The top 3 cm of sediment was sampled in triplicate using a washed 5 ml metal-capped glass bijoux jar, with its rubber seal removed, and applied as a miniature corer (Figs 3a & b) at the most recent strandline, avoiding springtide lines containing areas of non-representative historical accumulations (Fig 3c). Previous studies have reported finding more particles at the high-water mark compared to the low-water mark during a given tidal cycle, and are the justification for the choice of sampling regime applied in this study (Van Cauwenberghe et al., 2015). Efforts to minimize contamination during sampling in the field included avoiding clothing containing synthetic fibres (e.g. fleeces), sampling into the wind (avoids fibres blowing off clothing) and the use of a dampened 10 cm fibre glass filter exposed to the elements to give an indication of potential atmospheric deposition during sampling (Woodall et al., 2015; Crawford and Quinn, 2017a). The plastic particles were extracted from the collected sediment using a density separation protocol based on the method of Thompson et al. (2004). The sediment was vigorously agitated for 30 seconds using a magnetic stirrer in a saturated NaCl solution (384 g L^{-1}), and left to stand for 2 min to allow the sediment to settle out. The top half of the solution was then carefully vacuumed off into a glass round-bottomed boiling flask using a glass pipette connected via a silicone hose to a vacuum pump (Fig 4a). The extracted NaCl solution containing the microplastics was then filtered under vacuum through a glass fibre filter (Fisherbrand, pore size: 0.7 µm) (Crawford and Quinn, 2017b) (Fig 4b). The filters were placed under cover in petri dishes to dry overnight. Each sediment sample went through two washes after which the results were pooled. The sediment was dried in porcelain crucibles, weighed and the plastic content expressed as particles or fibres per gram sediment. Filters were examined under a high-powered Leica MZ75 dissecting microscope, and the suspected microplastics sorted in terms of shape (fibres or particles) and colour, counted and placed on to fresh filters – examples of microplastic particles and fibres can be seen in Fig 5a & b). In order to minimise and monitor contamination during laboratory analysis, clean clothing not made of synthetic fibres were worn, the work surface was wiped clean and a clean fibreglass filter was placed in a petri dish on the work bench during every session. Polymer identification was carried out by flattening the microplastics in a Perkin Elmer press before applying Fourier-Transformed Infra-Red spectroscopy (FT-IR; Perkin Elmer Multiscope/Perkin Elmer Spectrum 100) at a range of 600 – 4,000 cm^{-1}. Spectra were compared with those generated from weathered plastic of known polymer types and using the 'finger print' regions of the spectrum to identify the polymers (Dr Fionn Murphy, pers comm) (Fig 5c).

2.3 Data reduction and statistical analysis

Maps were produced from GPS coordinates using ArcGIS. Replicate sample means for microplastic particles and fibres from Orkney were compared against each other for each site. Mean data from all Orkney samples were compared against mean data generated from Erskine Bay and the Firth of Forth. All mean comparisons were analysed using a One way ANOVA followed by a Tukey multiple comparison test (SPSS Statistics 22). The effect of site characteristics on microplastic distribution were analysed by principle component analysis (PRIMER 6). Tested parameters: grain size, presence or absence of effluent and/or industry, proximity to centres of population, and the degree of shore exposure using the littoral sediment section of JNCC's National Habitat Classification for Britain and Ireland (CONNOR et al., 2015).

3. Results

3.1. Particle and fibre concentrations

Microplastic particles and fibres were found in every replicate intertidal sediment sample at each of the sites visited in Scapa Flow, averaging 730 and 2,300 kg^{-1} sediment (DW), respectively (Fig 6a). With two exceptions (Dead Sands and Mill Bay), plastic fibres significantly outnumbered plastic particles (Fig 6a). The sites with the highest fibre or particle concentration were Congesquoy and the immediately adjacent Dead Sands, respectively (Fig 6a). PCA analysis showed these two sites clustered together clearly separating them from the other Scapa Flow sites, the two components shown accounting for 92% of the variance in the data set (Fig 7). The fibre and particle concentration data generated from the Scapa Flow samples were compared against those from two highly populated industrialized Scottish locations in the Clyde and the Firth of Forth, sampled in the same way in February and April, 2016, respectively (Figs 6b & c). The average fibre concentration recovered from all samples collected from the Clyde and the Firth of Forth was significantly higher than the particle concentration, whilst there was no statistically significant difference between average particle and fibre concentrations in Scapa Flow. The average site concentrations for particles and fibres across the three locations (Scapa Flow, Clyde, Firth of Forth) did not differ significantly (Fig 6b). However, the maximum particle and fibre concentrations recorded at each location showed an interesting pattern. Scapa Flow and the Clyde had similar concentrations of fibres, but the maximum particle concentration was significantly higher in the Scapa Flow samples. Compared to the Firth of Forth, Scapa Flow sediments also contained significantly higher concentrations of both particles and fibres. The maximum concentration of particles recovered from the Clyde was significantly higher than those in the Firth of Forth, but there was no difference in fibre concentrations between the two locations (Figs 6c).

3.2. Contamination

The contamination monitoring filters put out on the beach during sediment sampling contained only sand and the occasional piece of seaweed debris, but no plastic. The filters put out on the work bench during sample analysis contained synthetic fibres, red in colour, on only one occasion that was traced back to the dust cover of the microscope. No similar fibres were found in the sediment samples.

3.3. Colour

The predominant colours of the recovered fibres were as follows: blue > black > purple = white > red > brown > green; for recovered particles: blue > red > yellow > black > orange > white > purple > brown = silver (Table 2).

3.4. Polymer type

Of the 116 items analysed from the Orkney samples 105 were positively identified as a known polymer. 45% were poly(tetrafluoro)ethylene, 15% polyethylene or polyvinylidine, 10% polyamide, 8% polyesther and 3% polyacrylonitrile or polydimethylsiloxane (Fig 8).

4. Discussion

The survey of intertidal sediments in Scapa Flow showed that microplastics were present throughout the entire system, an observation consistent with the ubiquitous nature of microplastics in the marine environment. Although there was some variation between the sampled sites in terms of concentrations found, microplastic fibres were generally more abundant than particles - the exceptions in the present study were Dead Sands and Mill Bay (Fig 6a). There are only very few published studies that have reported microplastic particles and fibres from the same intertidal sediment sample. One reason for this is the difficulty in distinguishing them from other natural and artificial non-plastic fibres, such as cellulose, cotton and plant material, without the application of expensive analytical techniques, such as Raman or FT-IR spectroscopy, which may not always be available, and, until automation can be suitably refined (Primpke et al., 2017), remains a time-consuming activity. Weathering and the formation of biofilms on immersed plastic surfaces can distort the FT-IR spectrum to such an extent that the polymer type becomes unidentifiable or produces unreliable results. In the present study, the use of the widely used Hummel polymer library proved unsuitable, because 90% of the particles and fibres analysed were returned as cellophane, a derivative of cellulose, and currently not considered a plastic. Running the same spectra against a library consisting of spectra obtained from plastic material of known polymer type and weathered in the marine environment decreased the failure rate to 9%. Brightly coloured fibres are usually confidently described as “plastic”. However, although colour can provide useful initial descriptive information about the material recovered, without definitive spectral information, conclusions can be subjective. Depending on the light-intensity, angle of observation and the microscope used, particles and fibres can appear as one colour or another. Furthermore, it was observed in the present study that some fibres seemed to change their colour during the flattening process in preparation for FT-IR analysis. For example, fibres which looked blue before flattening seemed to be white afterwards, or previously black fibres seemed to turn blue or purple. For these reasons, the colour was only determined at the first sorting and counting step, but was not a reliable indicator for polymer type (Tab. 3). Another reason for not reporting fibres in many intertidal microplastic surveys maybe the risk of contamination from atmospheric fallout and clothing worn by the researchers (Fries et al., 2013; Nuelle et al., 2014; Clunies-Ross et al., 2016). In the present study steps were taken at every stage to mitigate contamination-related artefacts in the data by sampling in to the wind, avoiding certain clothing prone to shedding fibres (especially fleeces) and monitoring atmospheric deposition during sampling, extraction and analysis (see methods). Those studies that have itemized fibres and used the NaCl flotation technique have observed similar fibre:particle proportions in sediment samples, e. g., along the Belgium Coast (Claessens et al., 2011), Northern coast of Taiwan (Kunz et al., 2016), the south-eastern coastline of South Africa (Nel and Froneman, 2015), and on Slovenian shores (Laglbauer et al., 2014). However, using modified density separation methods, other studies have reported mixed results. Alomar et al. (2016) found more fibres than particles only in sites close to populated areas, which was also observed in the present study. Wessel et al. (2016) found only one of the sites sampled in the Gulf of Mexico to contain more fibres than particulate microplastics, and De Carvalho et al (2016) reported the concentrations of microplastic fibres to be the smallest type cohort in intertidal sediments collected from Guanabara Bay, Brazil, the latter possibly reflecting climate-related clothing use in the area. Stolte et al. (2015), using $CaCl_2$ to extract microplastics found on average no major difference between sites sampled on German Baltic shores, but reported a major seasonal fibre spike in the summer which was attributed to increased beach use during the holiday season. Yu et al. (2016) also established a link between recreational beach use and microplastic concentration in intertidal sediments.

Most available studies have used some form of non-plastic sampling device to scoop or core sediment, some have included an onsite sieving step (Crawford and Quinn, 2017a), and employed a density separation protocol using NaCl (Besley et al., 2017; Crawford and Quinn, 2017b). In the present study, 5 mL glass tubes were used as corers to sample sediments. Sieving was not employed following the observation in preliminary studies that fragile microplastic fibres tended to break under mechanical agitation, thus artificially inflating the apparent numbers – this was also the reason why only two washes were performed per sample. Triplicate sediment samples served to dampen the variability at each site, from which microplastics were extracted using a saturated NaCl solution. Previous surveys conducted on comparable North Sea shores in Belgium and Germany found on average 156 and 671 particles kg^{-1} sediment, respectively (Claessens *et al.*, 2011; Liebezeit and Dubaish, 2012), which is a similar order of magnitude to the present study. Whilst the mean microplastic fibre concentration in Scapa Flow intertidal sediments (2,300 fibres kg^{-1} sediment) were similar to those recorded from the Firth of Forth and the Clyde using the same sampling methods (Fig 6), they were considerably higher than those reported in other comparable studies, 66 and 50 fibres kg^{-1} sediment (Claessens et al., 2011; Liebezeit and Dubaish, 2012), respectively. Whilst local site characteristics and modified sampling regimes may explain some of the differences, contamination in the present study cannot be completely ruled out, despite best efforts at mitigation (see above & methods). The use of NaCl is likely to underestimate the presence of certain polymers with a density >1.202 g cm^{-3}, such as PVC (1.35-1.70 g cm^{-3}), PET (1.40-1.50 g cm^{-3}) and PTFE (2.10 – 2.30 g cm^{-3}). Other groups have experimented with denser solutions, such as ZnCl and NaI, with densities of 1.5 -1.7 g cm^{-3} and 1.8 g cm^{-3}, respectively (see review in Crawford & Quinn, 2016b). Nevertheless, NaCl remains a popular choice, because of ease of use, no requirement for time-consuming recycling and waste management procedures and low cost (Besley et al., 2017; Crawford and Quinn, 2017b). Furthermore, increasing the solution density also increases the floatation of other non-plastic debris making the separation process less efficient, and therefore the NaCl method is considered an acceptable trade-off. Generally, the lack of standardized sampling and extraction procedures, as well as particular local conditions, does not allow meaningful comparison between studies, and makes drawing general conclusions about the reasons for observed microplastic concentrations at different locations around the world almost impossible. The spatial patterns of microplastic distribution in intertidal sediments in Scapa Flow appear driven by two main factors: hydrographic conditions and proximity to concentrations of anthropogenic activity. The more exposed sites at Creekland, Quoys, Lyrawa, Swanbister and Waulkmill had comparatively lower concentrations of microplastic particles than the more sheltered sites of Congesquoy, Dead Sands, Scapa, Mill Bay, Kirkhope and Widewall, which is consistent with the latter being predominatly sites of deposition (see grain size analysis, Tab 4). A similar observation was made for the spatial distribution of microplastic fibres, with the exception of Mill Bay and Creekland, which showed the opposite. Local anthropogenic activity plays a major role in determining the microplastic fibre concentration in the sites surveyed. The high concentrations of fibres at Congesquoy is highly likely connected to the wastewater treatment plant at Bu Point that services Stromness and discharges 750 m^3 per day into the Bay of Ireland (Scottish Water, pers comm). Commercial and domestic wastewater (Browne et al., 2011; Carr et al., 2016; Murphy et al., 2016), as well as areas of high population density (Alomar et al., 2016) have previously been identified as a source of microplastic fibres. The proximity of the Congesquoy site to Stromness (pop: 2,000 in Stromness proper; 3,000 in the wider Parish), local wastewater discharge and the particular hydrographic conditions in the Bay of Ireland (Fig 2) are therefore considered the most likely reasons for the high concentrations of microplastic fibres found. The exception here is the site at Cumminess, situated between Congesquoy and Dead Sands (Fig 1) that displayed microplastic particle and fibre concentrations more akin to an exposed site (Fig 7), and is possibly connected to the local hydrographic conditions (Fig 2). The results also suggest that microplastic fibre contamination in the area is largely autochthonous, whereas microplastic particles are more mobile and ephemeral, and likely to originate from diffuse allochthonous sources. Orkney is known to accumulate large amounts of marine litter on its shores (Catherine Gemmell, MCS, per comm) and the mainly irregular fragments found in the present study indicate secondary microplastic particles resulting from degradation of larger

pieces of flotsam as the most likely source. An exception here might be the sampling site at Mill Bay and its proximity to a salmon farm and the busy peer at Lyness (Fig 1).

5. Conclusions

Orkney, despite its relative remoteness and comparatively small human population, has intertidal sediment loads of microplastic particles and fibres comparable to locations on the UK mainland with much higher anthropogenic activity. It is clear that the data presented here is merely a snap shot, lacking any information of potential seasonal variability and temporal trends, without which assessing the impact of Government policies aimed at reducing (micro)plastic contamination in the marine environment will not be possible. Therefore, appropriate funding needs to be made available to enable the establishment of a baseline microplastics database and long-term monitoring programmes (Xanthos and Walker, 2017). Furthermore, inter-comparison exercises are required to harmonize methods (Rochman et al., 2017) and enable large-scale spatial comparison of sampling and extraction techniques, as well as standard operating procedures for comparable substrates, including the recording of site descriptive metadata.

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Table 1: Sampling locations and GPS coordinates, Scapa Flow, Orkney

Location	ID	Latitude	Longitude	Island
Congesquoy	OCo	58.974545	-3.2601566	Mainland
Cumminess	OCu	58.972044	-3.2420287	Mainland
Dead Sand	OD	58.975676	-3.2491173	Mainland
Scapa	OSc	58.96035	-2.9698181	Mainland
Swanbister	OSw	58.924308	-3.1282498	Mainland
Waulkmill	OWa	58.941914	-3.0806194	Mainland
Widewall	OWi	58.808793	-2.9793972	St. Margret's Hope
Creekland	OCr	58.917274	-3.3244757	Hoy
Kirkhope	OK	58.786881	-3.1540100	Hoy
Longhope	OLo	58.786381	-3.2583469	Hoy
Lyrawa	OLy	58.869486	-3.2286917	Hoy
Mill Bay	OM	58.837617	-3.2118833	Hoy
Quoys	OQ	58.908478	-3.3177673	Hoy

Table 2: Colour distribution of fibres and particles recovered from collected sediments

	Blue	Black	Red	Purple	white	green	orange	brown	silver
Fibres									
Congesquoy	45 (13)	6 (5)	10 (11)	34 (31)	24 (22)	0 (0)	-	16 (37)	-
Cumminess	32 (9)	4 (3)	4 (4)	11 (10)	10 (9)	1 (33)	-	2 (5)	-
Dead Sand	6 (2)	48 (37)	7 (8)	1 (1)	9 (8)	0 (0)	-	3 (7)	-
Scapa	39 (11)	15 (12)	3 (3)	4 (4)	6 (5)	0 (0)	-	10 (23)	-
Swanbister	20 (6)	2 (2)	10 (11)	5 (5)	1 (1)	0 (0)	-	1 (2)	-
Waulkmill	24 (7)	8 (6)	11 (12)	4 (4)	11 (10)	0 (0)	-	0 (0)	-
Widewall	31 (9)	8 (6)	13 (15)	6 (5)	5 (5)	0 (0)	-	2 (5)	-
Creekland	53 (15)	6 (5)	5 (6)	8 (7)	4 (4)	0 (0)	-	3 (7)	-
Kirkhope	46 (13)	12 (9)	6 (7)	20 (18)	15 (14)	0 (0)	-	2 (5)	-
Longhope	16 (5)	5 (4)	4 (4)	4 (4)	8 (7)	0 (0)	-	1 (2)	-
Lyrawa	13 (4)	5 (4)	5 (6)	9 (8)	3 (3)	1 (33)	-	2 (5)	-
Mill Bay	14 (4)	4 (3)	4 (4)	1 (1)	9 (8)	0 (0)	-	0 (0)	-
Quoys	12 (3)	7 (5)	7 (8)	3 (3)	5 (5)	1 (33)	-	1 (2)	-
Particles									
Congesquoy	13 (7)	0 (0)	8 (26)	2 (50)	1 (17)	9 (69)	0 (0)	1 (100)	0 (0)
Cumminess	0 (0)	0 (0)	1 (3)	2 (50)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Dead Sand	140 (79)	0 (0)	1 (3)	0 (0)	2 (33)	1 (8)	0 (0)	0 (0)	0 (0)
Scapa	0 (0)	0 (0)	9 (29)	0 (0)	0 (0)	1 (8)	1 (14)	0 (0)	0 (0)
Swanbister	1 (1)	0 (0)	2 (6)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Waulkmill	2 (1)	0 (0)	0 (0)	0 (0)	0 (0)	1 (8)	0 (0)	0 (0)	0 (0)
Widewall	2 (1)	1 (13)	1 (3)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	1 (100)
Creekland	4 (2)	1 (13)	2 (6)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Kirkhope	3 (2)	0 (0)	5 (16)	0 (0)	0 (0)	1 (8)	6 (86)	0 (0)	0 (0)
Longhope	1 (1)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Lyrawa	0 (0)	2 (25)	1 (3)	0 (0)	2 (33)	0 (0)	0 (0)	0 (0)	0 (0)
Mill Bay	11 (6)	0 (0)	0 (0)	0 (0)	1 (17)	0 (0)	0 (0)	0 (0)	0 (0)
Quoys	0 (0)	4 (50)	1 (3)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)

(..) percent recovered at each site

Table 3: Polymer ID of different coloured microplastic fibres recovered from Scapa Flow intertidal sediment

	Colour						
Polymer	**black (15)**	**blue (49)**	**brown (11)**	**green (2)**	**purple (13)**	**red (14)**	**white (8)**
POLYACRYLONITRILE	24%	-	-	-	7%	7%	-
POLYDIMETHYLSILOXANE	-	-	-	-	-	-	13%
POLYETHYLENE	13%	19%	-	-	15%	-	-
POLYTETRAFLUOROETHYLENE	34%	52%	-	-	38%	50%	13%
POLYVINYLIDENE	27%	16%	41%	-	7%	14%	-
POLYAMIDE	-	-	59%	100%	15%	7%	13%
POLYESTER	-	12%	-	-	7%	-	38%

(..) number of individual fibres analysed

Table 4: Grain size analysis of the sediment sampling sites

Station	Longhope	Lyrawa	Quoys	Mill Bay	Kirkhope	Creeklands	Dead Sands	Congesquoy	Scapa	Swanbister	Waulkmill	Wide Wall	Cumminess
pebble	0.00	0.00	1.73	6.35	5.56	0.00	0.00	0.00	0.00	0.00	2.55	1.27	0.00
granule	0.00	0.00	1.66	3.26	10.77	0.00	0.00	0.00	0.00	0.00	0.89	0.45	0.00
V. coarse sand	0.00	0.00	1.46	0.87	3.25	0.00	0.00	0.00	0.00	0.00	1.29	0.64	0.00
Coarse sand	17.26	45.99	48.04	23.89	2.12	43.32	13.45	4.00	3.88	20.18	21.65	10.99	15.82
Medium sand	55.13	37.18	46.17	52.00	39.70	49.59	53.99	74.32	77.49	66.71	61.53	58.26	65.20
Fine sand	26.08	14.89	0.94	12.63	37.63	7.09	30.34	21.68	18.63	13.11	12.09	28.34	18.91
V. fine sand	0.49	1.94	0.00	0.12	0.98	0.00	1.33	0.00	0.00	0.00	0.00	0.05	0.06
Silt Clay	1.04	0.00	0.00	0.87	0.00	0.00	0.89	0.00	0.00	0.00	0.00	0.00	0.00
	100	100	100	100	100	100	100	100	100	100	100	100	100

Figures in %

Figure captions

Figure 1: Map of the sampling locations around Scapa Flow, Orkney.

Figure 2: Tidal flow model of Scapa Flow. Vectors at hourly intervals referenced to highwater at Widewall Bay. A) Hightide; B) Lowtide.

Figure 3: Field sampling. A) using a 5mL glass bijoux jar as a corer; B) sample replication; C) example of the most recent tidal strandline at one of the sampling sites (Creeklands)

Figure 4: Sample processing: A) vacuuming off particles at the surface of the NaCl solution; B) filtering the collected supernatant under vacuum on to a 0.7 µm glass fibre filter.

Figure 5: Examples of microplastic fragments (A) and fibres (B) recovered; C) example of an FT-IR spectrum of pristine polyethylene (blue) and weathered polyethylene (red).

Figure 6: (a) comparing the mean (±SD; n=3) fibre and particle concentrations at the respective sites sampled in Scapa Flow; (b) comparing the mean (±SD; Scapa Flow n=13; Clyde n=10; Forth n=12) particle and concentration concentrations across three locations sampled; (c) comparing the sites with the maximum concentrations found at each location (means ±SD; n=3); *) donates significantly higher concentrations of fibres compared to particles; +) significantly higher maximum fibre concentrations compared to Firth of Forth ($p<0.05$; ANOVA).

Figure 7: Principle Component Analysis (PCA). The presented components account for 92% of the variance within the data set.

Figure 8: Proportion of polymer types of the 105 samples positively identifiable using FT-IR spectroscopy

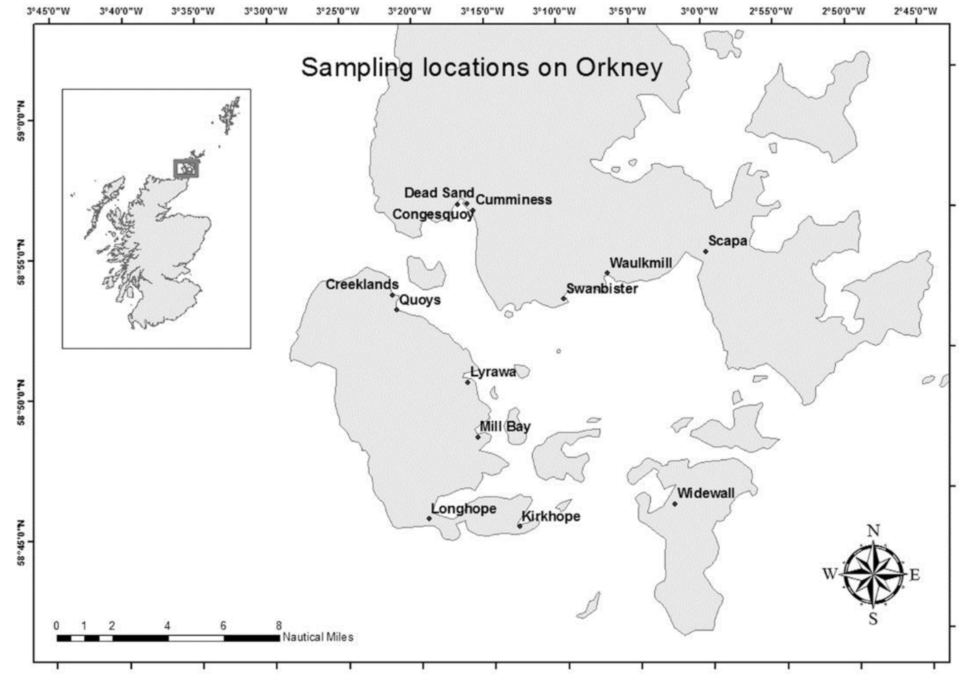

Sampling locations on Orkney
3°45'0"W
3°40'0"W
3°35'0"W
3°30'0"W
3°25'0"W
3°20'0"W
3°15'0"W
3°10'0"W
3°5'0"W
3°0'0"W
2°55'0"W
2°50'0"W
2°45'0"W
59°0'0"N
58°55'0"N
58°50'0"N
58°45'0"N
Dead Sand
Cumminess
Congesquoy
Scapa
Waulkmill
Swanbister
Creeklands
Quoys
Lyrawa
Mill Bay
Widewall
Longhope
Kirkhope
N
W
E
S
0 1 2 4 6 8
Nautical Miles

Fig. 1

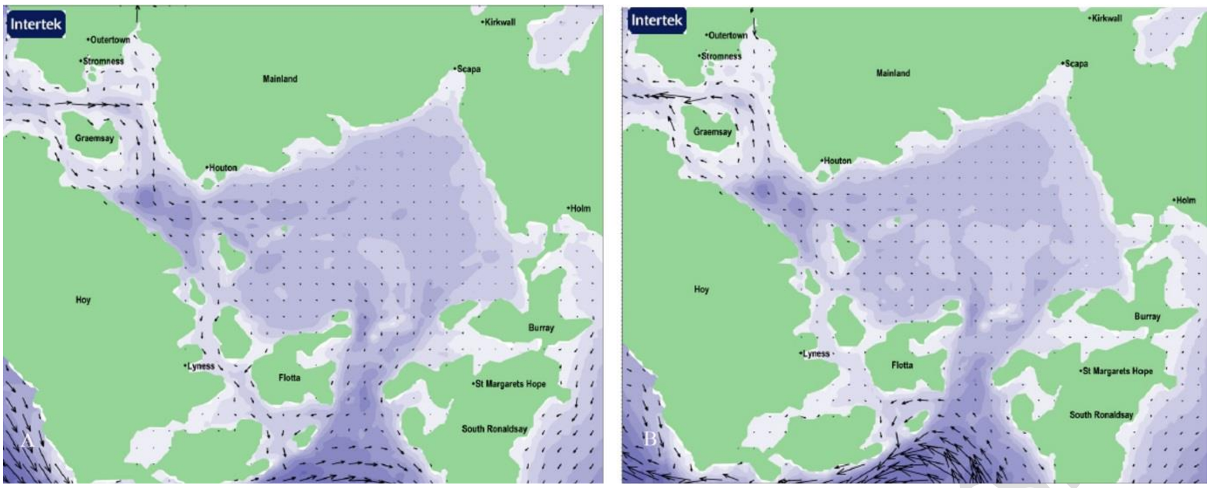

Intertek
Outertown
Stromness
Kirkwall
Scapa
Mainland
Graemsay
Houton
Holm
Hoy
Burray
Lyness
Flotta
St Margarets Hope
South Ronaldsay
A
Intertek
Outertown
Stromness
Kirkwall
Scapa
Mainland
Graemsay
Houton
Holm
Hoy
Burray
Lyness
Flotta
St Margarets Hope
South Ronaldsay
B

Fig 2

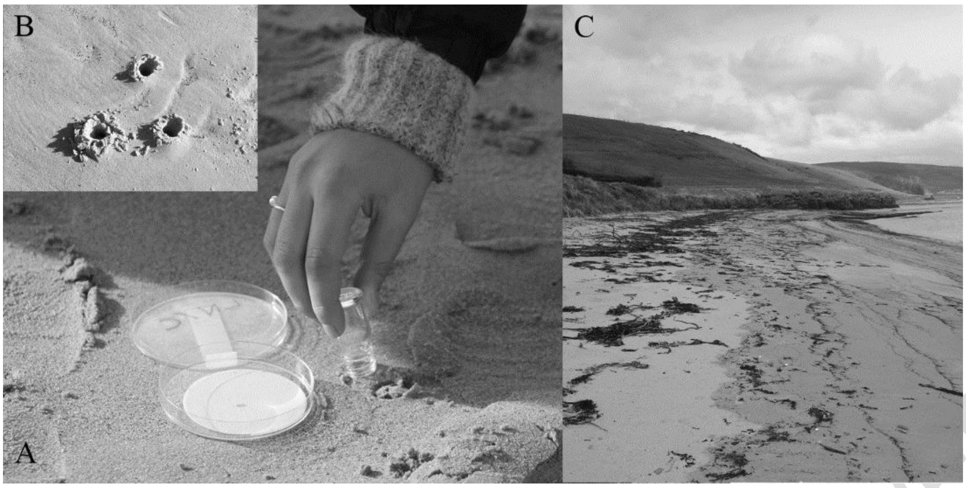


Fig. 3

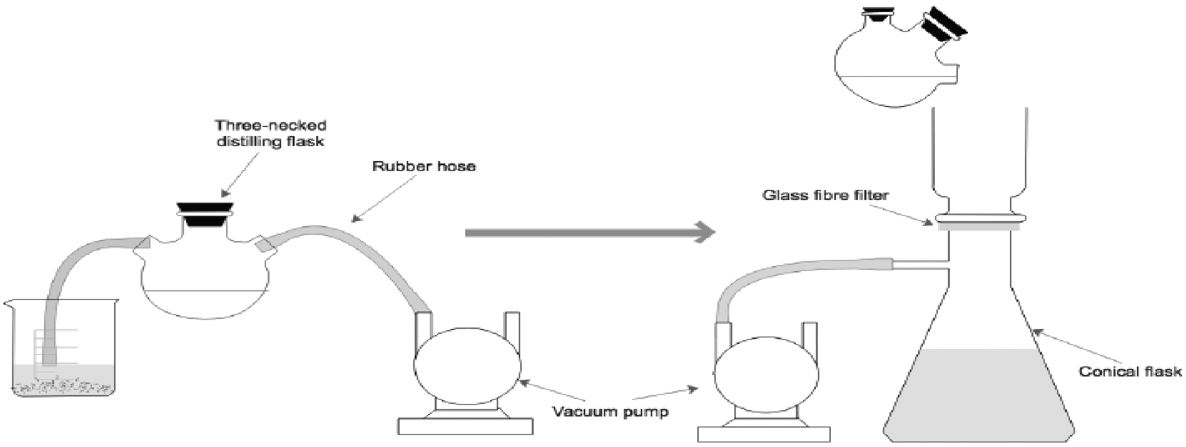

Three-necked
distilling flask
Rubber hose
Vacuum pump
Glass fibre filter
Conical flask

Fig 4

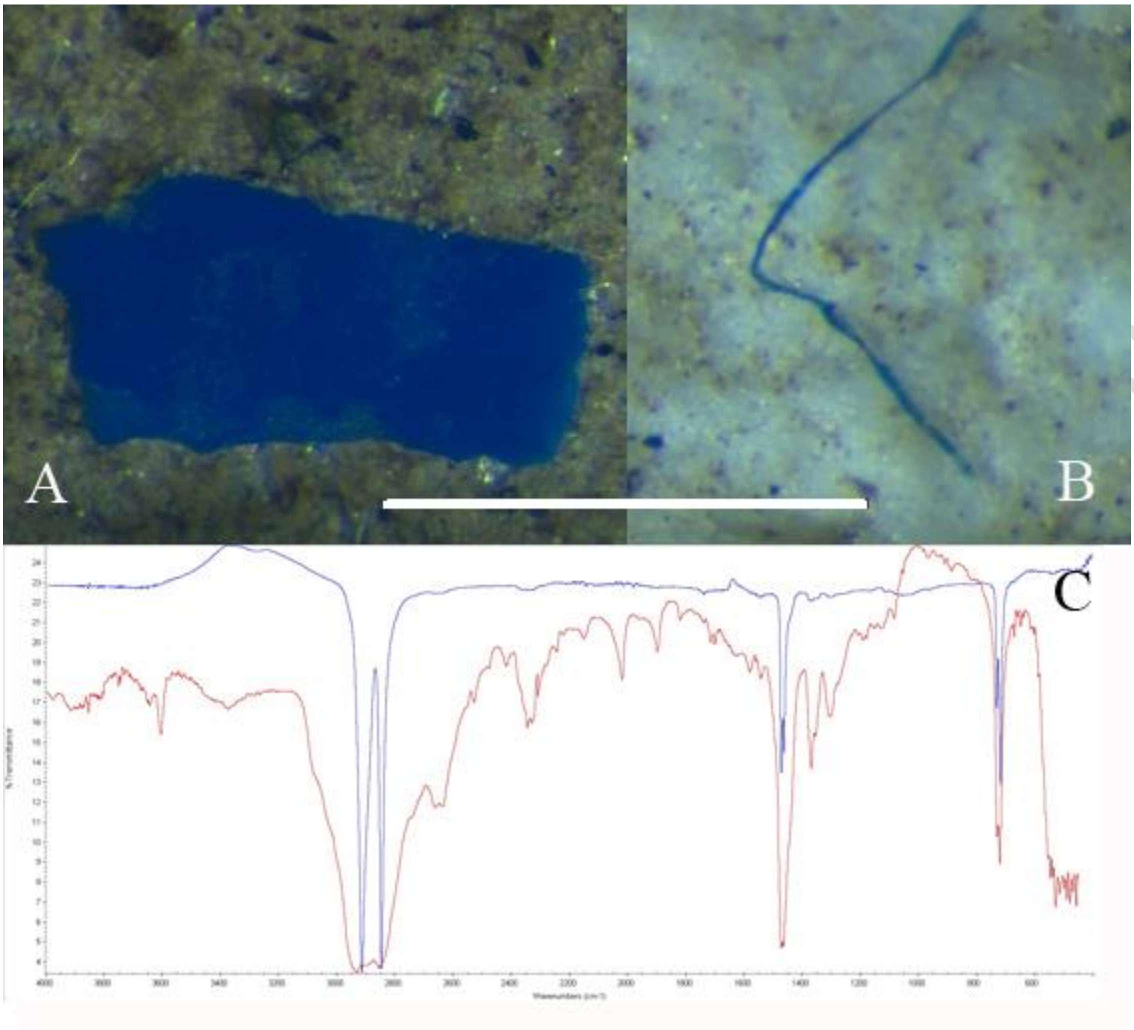
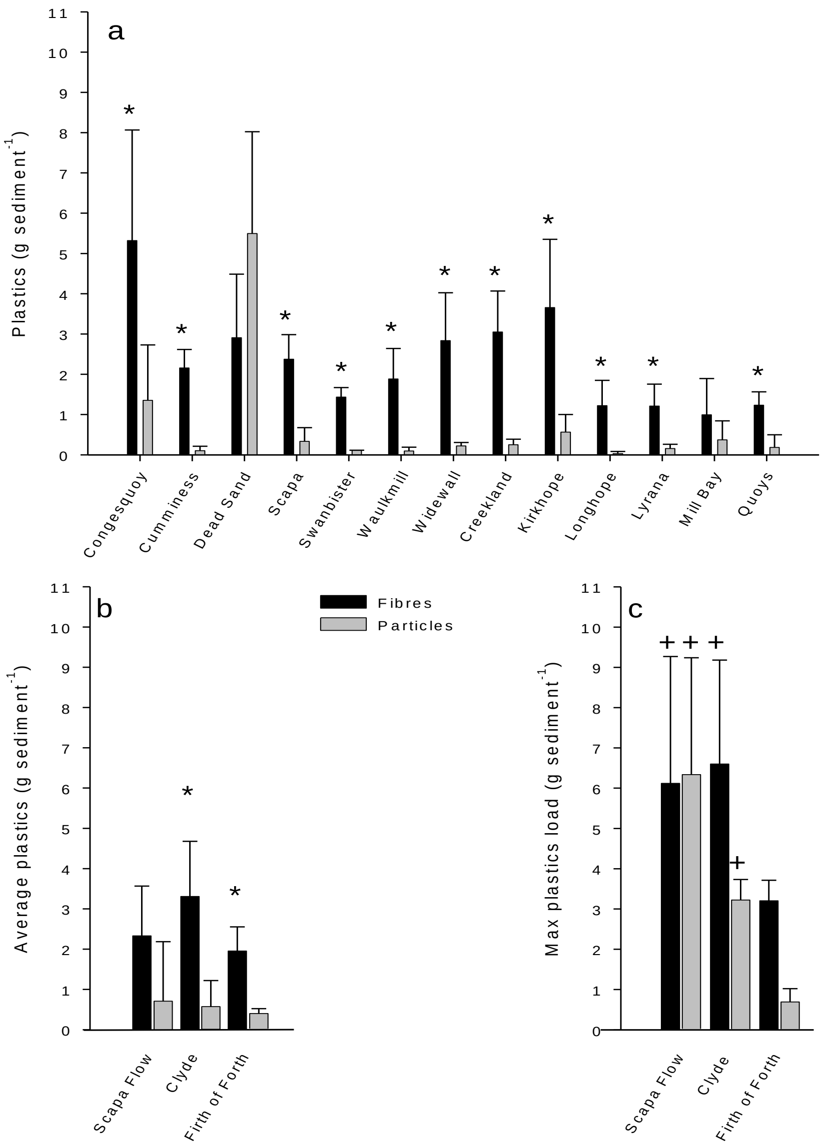
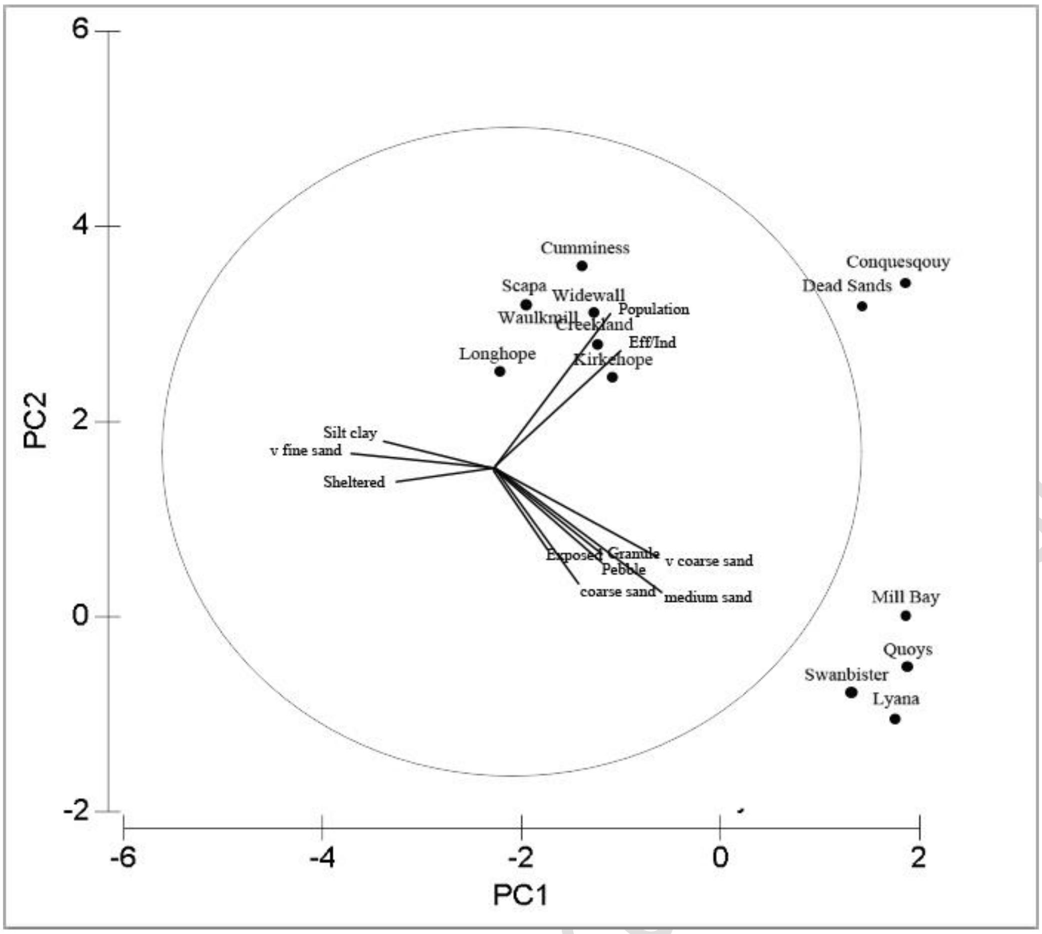


Fig 5



a
b
c
Plastics (g sediment^{-1})
Average plastics (g sediment^{-1})
Max plastics load (g sediment^{-1})
Fibres
Particles
Congesquoy
Cumminess
Dead Sand
Scapa
Swanbister
Waulkmill
Widewall
Creekland
Kirkhope
Longhope
Lyrana
Mill Bay
Quoys
Scapa Flow
Clyde
Firth of Forth

Fig 6



6
4
2
0
-2
PC2
-6
-4
-2
0
2
PC1
Cumminess
Scapa
Widewall
Waulkmill
Population
Creekland
Eff/Ind
Longhope
Kirkehope
Conquesqouy
Dead Sands
Silt clay
v fine sand
Sheltered
Exposed
Granule
Pebble
v coarse sand
coarse sand
medium sand
Mill Bay
Quoys
Swanbister
Lyana

Fig 7

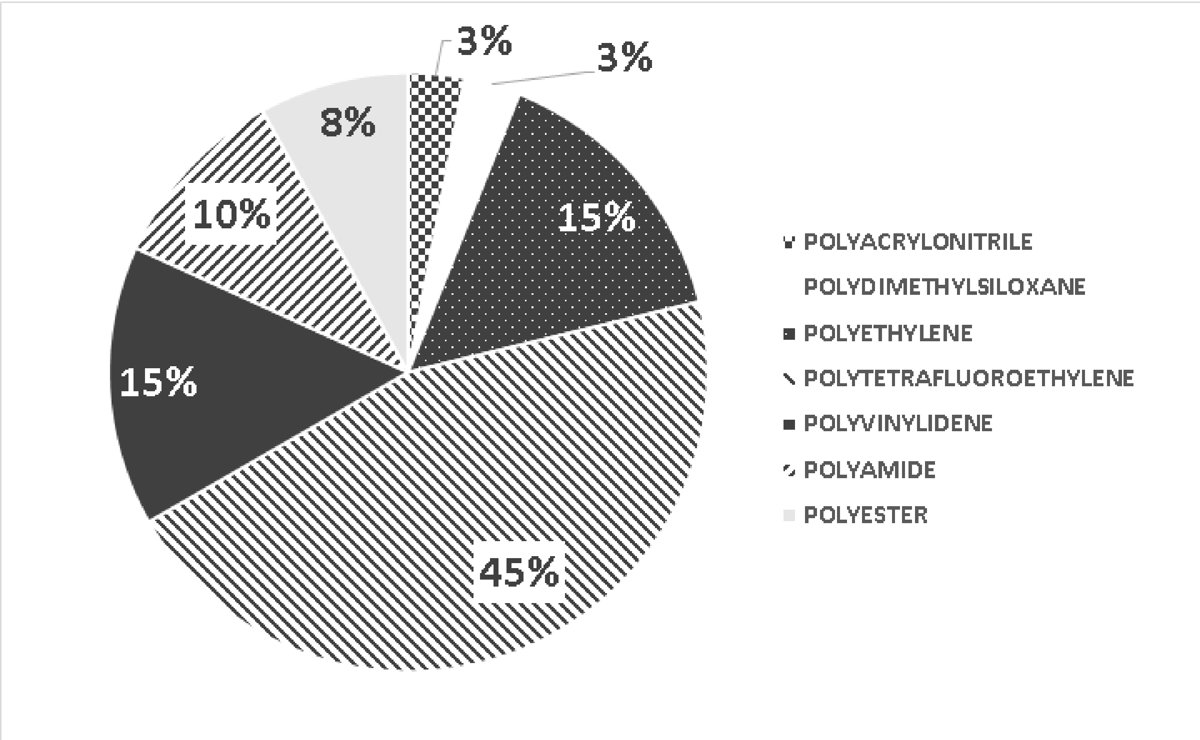

3%
3%
8%
15%
10%
15%
45%
POLYACRYLONITRILE
POLYDIMETHYLSILOXANE
POLYETHYLENE
POLYTETRAFLUOROETHYLENE
POLYVINYLIDENE
POLYAMIDE
POLYESTER

Fig 8